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A PILOTED SIMULATOR STUDY OF LONGITUDINAL HANDLING QUALITIES OF SUPERSONIC TRANSPORTS IN THE LANDING MANEUVER

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SUMMARY

A piloted simulator incorporating simulated visual cues in the landing maneuver was used in an exploratory study of several parameters pertinent to the stability and control characteristics of supersonic transports.

The result of pilots' assessments of speed-thrust instability in the landing approach, which is associated with the lift-drag characteristics of a low-aspect-ratio delta wing, indicated that the condition would not be tolerable for normal operation of a transport aircraft, but would be acceptable for emergency operation. Low values of static longitudinal stability were accepted; however, neutral static stability was considered tolerable only in an emergency condition. Pitch control sensitivity of the order of that of current large transport aircraft was desired.

Measurements of landing touchdown performance parameters from simulated landings indicated that no severe longitudinal control difficulties were apparent in the flare and touchdown maneuver over the limited flight conditions represented in the tests and for the range of variables considered. The great distance between the cockpit and the landing gear and the pitch attitude of the supersonic transport configuration at touchdown did not seem to present a serious problem in height judgment or longitudinal control.

The visual simulation was assessed as a significant contribution to handling qualities research; however, its successful application in these tests involved a substantial period of pilot training so that the visual cues could be used effectively in the absence of the cockpit motions experienced in flight.

INTRODUCTION

It is generally recognized that the high-speed performance requirements of supersonic transports will result in the adoption of unusual aerodynamic configurations. Previous experience with supersonic military aircraft has indicated that such configurations will probably have stability and control problems in several of the operational flight regimes and will require automatic stability augmentation equipment. In an effort to obtain information to aid the designer in defining the requirements for this equipment, a program of piloted simulator studies is being conducted at the Ames Research Center. The initial study, which was directed toward the stability and control problem areas in supersonic cruising flight, is reported in reference 1. The second phase of the program considers the problems of the low-speed flight regimes. This report presents the results of a simulator study of longitudinal control parameters in the approach and landing maneuver.

The objective of the landing tests was to study several SST control problems suggested by a comparison of the geometrical characteristics of a delta-winged supersonic transport (SST) design and a current subsonic turbojet transport. Figure 1 shows both airplanes oriented with respect to the ground plane as they would appear at touchdown, and table I presents a comparison of characteristics pertinent to longitudinal control in the landing approach. Two problems, primarily functions of size and mass distribution, are: (1) sluggish response in pitch with practical-sized control surfaces, and (2) possible inability of the pilot to control precisely ground contact conditions because of his extreme distance from the wheels and the ground at touchdown. Another problem arises from the basic aerodynamic characteristics of the low-aspect-ratio wing. If this aircraft is flown at high lift coefficients so that approach speeds will be low, the accompanying drag characteristics would require increased thrust with decreased airspeed when the aircraft is constrained to a specific approach flight path. Experience with this speed-thrust instability problem in a number of military aircraft cannot be applied directly to the supersonic transport because of the significantly differing operational requirements. There are also indications that high-speed performance considerations may dictate use of an SST geometry which has low static longitudinal stability at landing-approach speeds.

It is the intent of this investigation to examine these factors singly and in combination. It is generally agreed that no degradation of handling qualities from those of the current jet transport would be acceptable for normal operation of the supersonic transport. If, to meet this requirement, "black box" solutions are indicated, their acceptance will depend to a large degree on the severity of the consequences of failure of the automatic equipment. Therefore, it is necessary to define not only the handling qualities requirements for normal operation, but also those considered acceptable in the emergency condition of augmenter failure.

This study included the use of a visual simulator, which by means of a television camera, a runway model, and a projection system, provides the simulator pilot with a realistic view of the runway that accurately reflects the motions of his simulated airplane. The validity of results obtained in this fixed-cockpit simulator was investigated by a comparison of flight and simulator landing-performance measurements.

NOTATION

$\bar{c}$ wing mean aerodynamic chord, $\dfrac{\int c^2\,dy}{\int c\,dy}$, ft

C_D drag coefficient, $\dfrac{\text{drag}}{qS}$

C_L lift coefficient, $\frac{\text{lift}}{qS}$

$C_{L_{\infty}}$ lift coefficient in the absence of ground plane influence

C_m pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$

C_{m_α} longitudinal stability derivative, $\frac{\partial C_m}{\partial \alpha}$, per radian

C_{m_δ} control power derivative, $\frac{\partial C_m}{\partial \delta}$, per inch

I_y pitching moment of inertia, slug-ft^2

M_δ $\frac{S\bar{c}}{I_y} C_{m_\delta}$, radians/sec/in.

q dynamic pressure, lb/ft^2

S wing area, sq ft

T thrust, lb

V airspeed, knots

W airplane landing weight, lb

α angle of attack of fuselage reference line, radians or deg

δ longitudinal control column deflection, in.

ζ longitudinal short-period damping ratio

ω_n undamped longitudinal short-period frequency, radians/sec

TEST EQUIPMENT

Simulator

The simulator was designed to present the pilot with essential elements of the task of performing an ILS approach and landing under minimum visibility conditions. The transport-type cockpit (fig. 2) was equipped with normal flight controls and a flight instrument display representative of those found in current transport aircraft. The simulator did not incorporate cockpit motion. Control forces were provided by springs and dampers, and thus were functions of control displacement and rate only. Control column travel and control force gradient are defined in table I. The general purpose analog computer used with the simulator was programed with the equations of six degrees of motion freedom.

The visual simulation equipment (fig. 3) was designed by the Dalto Corporation for use with operational flight trainers. Approach lights and a runway, at a scale of 300 to 1, were moved on a belt toward a television camera which was servo-driven in the other five degrees of freedom. With this model scaling, the maximum visibility range was 3,000 feet, and the maximum visual excursions from the runway center line were 400 feet vertically and laterally. The resultant approach scene was presented to the pilot by means of television projection on a screen mounted 12 feet forward of the cockpit, providing a horizontal field of view of 45°. A standard 525 line TV system was used. The picture, obtained after some experimentation with lighting to provide the maximum visibility of the runway, most closely resembled a landing at dusk in thick haze. Approach and runway lighting, the runway surface, and the horizon are shown in a view looking through the windshield in figure 2.

Test Configurations

Reference airplane.- For purposes of simulator validation, a simulation of the Boeing 707-320 airplane was included in the tests. Considerable service landing performance data were available for this type of aircraft for comparative purposes (refs. 2 and 3). Also, it was felt that the longitudinal handling qualities of this aircraft, as represented on the simulator, would provide an appropriate reference from which to evaluate the characteristics of the SST configurations. The dynamic behavior of the 707, as determined from flight measurements, was faithfully represented by means of the computer. Control forces experienced by the pilot were, however, an approximation of those in the airplane, since the feedback of aerodynamic forces from the control surfaces could not be represented exactly with only the spring-damper system used in the simulation.

Supersonic transport.- The supersonic transport considered in the program was the delta-winged airplane with a canard control surface that is shown in figure 1. It should be pointed out that the SST described here was a particular design; however, the weight, length, and pitching moment of inertia are representative of a range of SST designs. Two values of speed-thrust stability used for the SST simulation corresponded to appropriate values of wing incidence, flap deflection, and minimum drag coefficient. Wing incidence was varied with flap deflection in order to prevent the introduction of a variation in fuselage attitude at touchdown. The lift and drag characteristics of the 707 and two SST configurations are presented in figures 4 and 5, respectively, and the resultant variations of thrust required with approach airspeeds are shown in figure 6. The high thrust levels shown for the SST reflect the low lift-to-drag ratio of the low-aspect-ratio wing, but most significant is the difference in the slope of the curves at the approach speed for the SST configurations and for the 707. For the configuration designated SST A, it can be seen that at a selected approach speed of 140 knots the thrust required increases as speed decreases, thereby producing a speed divergence if the aircraft is held to a fixed flight path. SST B exhibits an essentially neutral slope. The more conventional stable variation of thrust required with speed is shown for the 707.

The other variables assumed for the SST are listed in table II. A total of nine combinations of variables was included in at least part of the tests. The values of M_α correspond to static margins of 8, 4, and 0 percent. Two values of control sensitivity, M_δ, were considered, and were intended to reflect differences in the size of the longitudinal control surfaces, which would depend to some extent on the maximum static margin for which the airplane was designed. Natural frequency and damping ratio (at the approach speed), which are shown in the remaining columns, are descriptive of the longitudinal dynamics of the aircraft. It can be noted that while the characteristics of SST configuration B1 do not differ greatly from those of the 707, the other configurations include lower natural frequencies and lower control sensitivity as well as speed-thrust instability. Since the objectives of these tests were limited to the study of longitudinal characteristics, lateral-directional handling qualities were set at a satisfactory level. The effects on lift and pitching moment of the presence of the ground, as simulated for the test configuration, are shown in figure 7. For all of the tests, engine thrust response to throttle movements included a first-order time constant of 1.3 seconds.

TESTS AND EVALUATIONS

The test program was conducted in two phases. Initially, all of the test configurations were subjectively evaluated by the pilots in a simulation of a minimum visibility ILS approach, from interception of the glide path to landing. The second phase involved a more critical look at the climax of the maneuver, the flare and touchdown. For this phase of the tests, measurements of landing performance were the primary evaluation criterion.

Three NASA pilots and one FAA pilot contributed to this program. All were experienced test pilots, but they had widely different experiences with large transport aircraft. Flight and simulator experience of these pilots is included in table IV. Each had the opportunity to familiarize himself thoroughly with the operation of the simulator with 707 characteristics represented. The SST configurations were presented to the pilots in varying order to avoid a uniform effect of learning on their evaluations. Each configuration change presented to the pilot involved a change of only one of the variables. The pilots were asked to assign a numerical rating of the longitudinal handling qualities to each configuration in accordance with the schedule shown in table III. In this schedule, "primary mission" refers to the complete minimum-visibility instrument approach and landing using standard ILS guidance. The last column of this rating schedule "can be landed" refers to a landing under visual approach conditions.

Instrument Landing Approach

The first simulated task consisted of intercepting the ILS flight path from level flight at 1,500 feet altitude with an initial lateral offset. The approach was continued until visual contact was made with the runway at about

200-feet altitude, and then a landing was performed. Crosswinds up to 10 knots were included in a majority of the approaches to increase the realism of the task.

It was expected at the inception of this program that the ILS approach task would be sufficiently demanding that variations in pilot opinion would be accompanied by significant differences in glide-path tracking performance. A performance parameter was devised, and a large number of approaches were "flown" by one pilot. The results (ref. 4) gave a limited correlation of opinion and performance; however, as in many previous efforts at correlation of pilot opinion and performance, measured differences were small. For the remainder of the tests, it was decided to forego further performance measurements in the ILS task.

Flare and Touchdown

Initially, it was desired to obtain evidence to indicate that with the simulation of the 707 aircraft the landing maneuver could be performed with reasonable facility and in a manner analogous to flight. In the few seconds of the final visual portion of a minimum visibility landing, the pilot has a firm, single-minded objective - to hit a particular portion of the runway as softly as possible. If it is assumed that for these few seconds the pilot is operating to his maximum capacity as a control element, measurements of his performance in terms of touchdown rate of descent and dispersion along the runway should reflect the effectiveness of the simulation and the relative handling qualities of various simulated aircraft. Touchdown performance measurements have been obtained for current jet transports in airline service (refs. 4 and 5) and include the results of hundreds of landings. These data are considered a valid basis of comparison for evaluation of the simulated landing performance.

Three of the SST stability and control configurations were considered in the landing tests. These were chosen from the less satisfactory combinations in order that the greatest number of potential problems might be exposed with a reasonable amount of testing. They were (table II) configurations B3 ($[\partial(T/W)]/\partial V = 0$, $\partial C_m/\partial C_L = 0.04$), A3 ($[\partial(T/W)]/\partial V = -0.0012$, $\partial C_m/\partial C_L = 0.04$), and A5 ($[\partial(T/W)]/\partial V = -0.0012$, $\partial C_m/\partial C_L = 0$).

The simulated landing approaches were initiated at an altitude of 500 feet. Random small offsets from the ILS glide path (100 feet laterally, 50 feet vertically) were programed in the starting conditions in an effort to simulate the small dispersions that would normally exist at this point in a visual approach, and a "flight director" presentation was used to the "break out" altitude of 200 feet to provide flight-path guidance of at least the quality afforded by visual cues under conditions of good visibility. No specific touchdown target point was presented; however, the ILS glide path to which the pilot was controlling while on instruments was adjusted to intersect the runway at a point 600 feet beyond the runway threshold, instead of the normally greater distance, in order to approximate more closely the good visibility flight path.

RESULTS AND DISCUSSION

Pilot acceptance of the landing simulation and some initial experiences with the equipment are discussed in an appendix to this paper. However, at this point it should be stated that all of the pilots found it difficult to perform landings at their first experience with the simulator. The test results presented in this paper represent capabilities of the pilots after each had accommodated to the simulation. At this time, the pilot felt that his performance was consistent, and the realism of the task was sufficient to demonstrate the normal landing parameters.

Instrument Landing Approach

Reference airplane.- From flight experience with 707 type aircraft, the low-speed longitudinal handling qualities were assigned a pilot opinion rating of 3, or "Satisfactory, with some mildly unpleasant characteristics." Contributing to the "mildly unpleasant characteristics" is a sluggishness in pitch which is a normal consequence of the aircraft's size and weight. This rating was generally confirmed on the simulator, and formed the basis for comparison on which ratings for the SST configurations were made. Pilot opinion ratings for all the SST combinations tested are summarized in figure 8 and are discussed below.

Speed-thrust stability.- For all of the combinations of static margin and control sensitivity tested, varying the parameter $\partial(T/W)/\partial V$ from 0 to -0.0012 caused an average increase in pilot rating of about one rating number. In all cases the degradation was severe enough to make the longitudinal control characteristics unacceptable for normal operation (pilot rating greater than 3-1/2). The pilots observed that this level of speed-thrust instability added a small but distinct task to his normal heavy workload in the instrument approach. It should be noted that speed-thrust instability was rated only after the pilot had optimized his technique for speed control. For the two pilots who had not experienced this characteristic in flight, it presented a serious control problem until they became familiar with it. The magnitude of the increase in pilot rating number accompanying the change in $\partial(T/W)/\partial V$ from 0 to -0.0012 agrees well with the results of simulator and flight studies reported in references 5 and 6, which include pilots' assessments of a wide range of speed-thrust stability characteristics in a small delta-winged airplane in a landing-approach task.

Static margin.- For constant values of the other parameters of the tests, reducing the static margin from 8 to 4 percent did not adversely affect the pilot rating (fig. 8), but reducing it to zero was detrimental to the handling qualities of the simulated aircraft. In view of the relatively small differences in the short period dynamic characteristics accompanying these changes in static margin (table II), it would appear that the pilots' ratings reflect the influence of static stability on speed control. The effect of neutral static stability is to eliminate the speed error cues which normally stem from out-of-trim control forces.

Control sensitivity.- The reduction in M_δ from 0.020 to 0.011, a value for which it is still possible to trim the aircraft if the static margin is 4 percent or less, resulted in a degradation of pilot rating at a static margin of 4 percent (fig. 8). A consensus of pilot comment indicated that the value of M_δ of 0.020, which approximates that of the 707, approaches the lower limit of desirable control sensitivity for the conditions of these tests. However, as shown in figure 8, pilots B and D preferred the lower control sensitivity at the condition of neutral static stability and speed-thrust instability. Their comments indicated that they felt the higher control sensitivity led to disturbing inadvertent pitch inputs during lateral maneuvering. One might speculate that lack of cockpit motion influenced this judgment since real angular acceleration cues would be expected to reduce inadvertent control inputs.

Flight director display.- During the course of these tests, several pilots were given the opportunity to perform approaches with a flight director display instead of the conventional ILS display. With the flight-path control task reduced to that of pitch and roll attitude tracking, the pilots had little difficulty performing satisfactory approaches with even the poorest configuration. As a result of the reduced pilot workload for flight-path tracking, much more effort could be devoted to speed control. Also, the improved flight-path tracking resulted in reduced speed perturbations. The pilots felt that with flight director guidance, the difficulty of the landing approach task did not change markedly over the ranges of parameters considered in the tests. It thus appears that this type of display might be used to land aircraft with unsatisfactory handling qualities in the event of failure of stability augmentation equipment.

In summary, the results derived from the instrument flight portion of the landing approach task lead to the following conclusions. Speed-thrust instability is not acceptable for normal operation of transport aircraft, but may be acceptable for emergency operation. Positive static stability is required, but probably more for speed trim characteristics than for dynamic response. Pitch control sensitivity of at least the order of that of the 707 airplane is desired.

Flare and Touchdown

Simulator validation.- Landing-performance measurements for 160 landings with the 707 aircraft characteristics simulated are compared with flight measurements in figure 9. These data are shown as the probability of equaling or exceeding a given value of vertical velocity, and a given distance beyond the threshold at touchdown. The flight data, taken in good visibility conditions (ref. 3), are representative of two of the largest turbojet transports, including the 707-320. These data are subject to all of the conditions of normal airline landings, including variations in weight, center-of-gravity position, and pilot experience; whereas the weight and c.g. position of the simulated airplane were not varied. In view of the differences, there was reason to expect less than perfect correlation between simulator and flight measurements, but it was felt that at least first-order agreement should be obtainable with any simulation that represents the important characteristics of the landing maneuver.

The results, particularly the touchdown rate-of-descent measurements, show good agreement. A mean value of 2.0 feet per second was obtained on the simulator, and a value of 1.9 feet per second was measured in flight. At the lower probabilities, the disparity was slightly greater. The 1-in-10 value from the simulator was 3.4 feet per second as compared with 3.0 feet per second in flight. The highest vertical velocity recorded on the simulator from 160 landings was 4.8 feet per second. From a total of 215 airline landings, the highest value recorded was 4.0 feet per second.

The touchdown point measurements shown in figure 9 do not show such good agreement; simulator landing distances averaged 1000 feet greater than those measured in flight. Initially, some concern was felt that dispersion indicated that the simulator pilot, in an effort to obtain low vertical velocities at touchdown, was compensating for poor visual cues by starting his flare prematurely and establishing low sink rates long before touchdown. The NASA flight data did not contain information regarding flight path prior to touchdown; however, an FAA publication, reference 7, was found to contain flight-path measurements of 183 jet transport landings, again under good visibility conditions. A description of the mean flare path, in terms of vertical velocity versus wheel altitude, for the simulated landings, is compared with that from the flight measurements in figure 10. Again, the results were encouraging, with this evidence indicating that the pilots were conducting their simulated flares in a manner similar to flight. A partial explanation for the long landings on the simulator is that the visibility conditions presented on the simulator induced the pilot to shallow his flight path slightly, as soon as he attempted to establish his visual cues at an altitude of about 200 feet. Mean altitude over the runway threshold on the simulator was 35 feet compared with 18 feet from the flight measurements.

While these observations account for the major part of the disparity between simulator and flight measurements of landing distances, there is evidence that a simulation problem is reflected in these data. The records show a tendency to "float" excessively between essential completion of the flare and touchdown. The lack of resolution in the visual presentation of the near surface of the runway probably forces the pilot to "feel" for the runway in the last few feet of descent as he might in a night landing without landing lights.

A time history of pertinent quantities measured during the performance of a simulated landing with the 707 configuration is presented in figure 11. Descriptive of the nature of the longitudinal control task are the relatively large amplitudes of the higher frequency components (0.5 to 1.0 cycle per second) of the control inputs compared with those of the low frequency, or trimming inputs. At this critical phase of flight, the pilot is exercising very tight control of his pitch attitude, and drives the aircraft in pitch at frequencies well above the short-period natural frequency of the aircraft (0.16 cycle per second). In this mode of control, control sensitivity and pitch damping tend to become more significant to the pilot than does static margin. Another item of interest is the variation of vertical velocity with time, indicating the very small incremented normal acceleration experienced in a normal landing flare, in this case, 2 feet per sec^2. The control of thrust is typical for the landings of this configuration from an approach speed of 132 knots (1.3 times the stall speed). The pilot hesitated to make large power reductions until the flare was essentially completed.

The results of the simulator validation tests with the 707 configuration, both the measurements and the pilot acceptance, indicated that the simulation meets the objective of providing a useful research tool. These results also provide a firm basis of comparison for the landing-performance data from the SST configurations.

SST landings.- Factors such as speed-thrust instability and low static margin did not have a first-order effect on conditions at the initiation of the flare because the landing runs were initiated under controlled conditions at the low altitude of 500 feet, and the pilot used a flight director display to control his descent to visual contact. This procedure served the objective of the tests, which was to assess the effects of the control characteristics and the extreme cockpit location on the flare and touchdown maneuver. The pilots had experienced the handling characteristics of the SST configurations during the ILS approach phase of the study. As a result, very little landing practice for familiarization was required. A total of 310 landings were recorded with the SST configurations; 240 of them by pilots A and B. The results of these landing tests can be succinctly summarized with the observations that the differences in SST configuration had little effect on the performance of the flare and touchdown maneuver, in terms of either pilot comment or measured performance, and that the SST configurations were landed with much the same facility as the 707 simulation. The 707 and cumulative SST performance measurements are compared in figure 12. The data for the SST configurations represent the cumulative performance of all four pilots with the performances of pilots C and D weighted as though they had participated equally with pilots A and B. The differences in the measured performances for the 707 and SST configurations cannot be considered significant. Figure 13 shows no evidence of significant performance differences between individual SST configurations in these data, particularly when it is remembered that each data sample represents, at most, 40 landings.

Figure 14 shows a comparison of the mean flare flight paths for the 707 and the SST configurations. There is little evidence that the cockpit location with respect to the wheels affects the flare. The data in figure 14, with the touchdown data, would indicate that the pilot's judgment of height and height rate does not suffer significantly at the increased cockpit altitude of the SST.

Pilots' comments regarding comparative handling qualities did not contradict their measured performances. There was a unanimous desire for higher control sensitivity, but the condition tested was not considered limiting. A consensus of observations would indicate that the lift-drag characteristics of the SST, which reduced the "floating" tendency and induced a more positive touchdown, compensated for any difficulty caused by the cockpit location. Neutral static stability caused no trouble at all for pilot A; pilot B stated he was disturbed by this factor, and his performance provided supporting evidence (configuration A5, fig. 13). In the opinion of the pilots, the effects of all the variables considered in the tests were minimized in the visual flight task.

Preliminary results from this landing study (refs. 8 and 9) showed a significant decrease in landing performance for the SST, which is contradictory to the results reported in this paper. The conclusions arising from these data, though qualified by their preliminary nature, were supported by the fact that they agreed with the preconceptions of the magnitude of the control problems. These results were influenced by inaccurate simulator performance, and a lack of sufficient pilot participation.

CONCLUDING REMARKS

Several general observations can be made from the simulator tests of longitudinal stability and control parameters pertinent to the low-speed operation of the supersonic transport. For the ranges of control parameters considered, no severe control problems were encountered, although it was possible to define the majority of conditions tested as being unsatisfactory for normal airline operation. Even the most objectionable combination of parameters tested, speed-thrust instability of -0.0012, and neutral static stability, was considered acceptable in an emergency. Surprisingly, the great distance between the cockpit and the wheels of the SST failed to present a problem to the pilot in the flare and touchdown.

The degree of correlation with flight performance obtained with the simulation of the 707 aircraft enhances the significance of SST handling qualities evaluations, but it should be remembered that this correlation, and the subsequent evaluations, depended largely on the considerable flight and simulator research experience of the test pilots involved, and their appreciation of the objectives of the tests.

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Moffett Field, Calif., Jan. 21, 1964

APPENDIX

COMMENTS ON SIMULATOR EFFECTIVENESS

All of the pilots who "flew" the visual landing simulation initially had some degree of difficulty performing the landing maneuver. With the artificialities inherent in the simulation, it was expected that the pilots would require some training to adapt to the simulator, but the nature and the persistence of the difficulties were not anticipated. The experienced test pilots required up to 10 hours of practice with the equipment to attain a stabilized, realistic level of landing performance. For tests such as those reported in this study, flight-simulator correlations and the use of simulator-trained pilots can provide the necessary confidence in the results, but for future experiments involving vehicle dynamics further removed from the pilot's flight experience, there is the danger that difficulties arising from the pilot's inexperience with simulator characteristics might be interpreted as arising from the characteristics of the vehicle being simulated. Thus, it is felt that greater understanding of the factors contributing to the extensive adaptation requirements will lead to even more effective use of this type of simulation. Although these factors are not yet clearly defined, two characteristics of the simulation undoubtedly contribute to the pilot's initial performance problems, deficiencies in the visual presentation and lack of cockpit motion.

VISUAL PRESENTATION

The deficiencies of the visual presentation are those associated with (1) the lack of resolution inherent in television projection, and (2) lack of peripheral visual cues. Difficulty in judging height just prior to touchdown apparently persists for some pilots, though others seem to compensate for lack of surface detail, with cues from the runway geometry. There is a tendency to complain of a lack of normal attitude sensing, due to the restricted visual field; however, flight tests have indicated that field restrictions of this magnitude do not reduce the pilot's ability to perform landings.

COCKPIT MOTION

There are reasons to suspect that the absence of cockpit accelerations is the primary cause of the pilot's initial confusion. The simulation uses outside world visual cues to present to the pilot a demanding six-degree-of-freedom task. The realism of this task can be expected to prompt reliance on flight conditioned reflexes, including those which involve vehicle accelerations. In a sense, then, a pilot in the fixed-cockpit simulator is initially analogous to a complex servo system in which some of the error sensors and stabilizing feed-back loops have been removed. This analogy is reinforced by examination of the control inputs during a pilot's early experience which indicates unrealistic overcontrolling tendencies. The attainment of realistic performance in the simulated landing task is a measure of the reestablishment of these "servo loops" by means of visual information only. It is not difficult to believe that such a relearning process could result in the difficulties experienced by the simulator pilots. It must be remembered that although angular acceleration information can be deduced from the strong angular velocity cues present in the visual display, there is little visual information that can be offered as a substitute for linear accelerations.

The need for studies aimed at defining the influence of cockpit motion over a wide range of flight tasks is recognized. Until these definitions are obtained, the effective research use of the type of simulation described in this paper will require very careful assessment of the significance of acceleration cues in each simulated task, and will benefit from the utilization of test pilots who have had the opportunity to attain and maintain proficiency with the equipment.

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TABLE I.- CHARACTERISTICS OF THE SIMULATED AIRCRAFT IN THE LANDING APPROACH

	707	SST
Weight, W, lb	180,000	210,000
Wing area, S, sq ft	2,894	5,500
Aspect ratio	7.0	2.17
Speed, V, knots	132	140
Lift coefficient, C_L	1.06	0.57
Fuselage angle of attack, α, deg	2.8	7.0
Pitching moment of inertia, I_y, slugs/ft^2	5×10^6	12×10^6
Control column travel, in.	8 aft, 6 forward	
Longitudinal control force, lb/in.	10	

TABLE II.- LONGITUDINAL CHARACTERISTICS OF TEST CONFIGURATIONS

Airplane	$\frac{\partial T/W}{\partial V}$	M_α	M_δ	ω_n	ζ
707	0.0012	0.58	0.023	0.98	0.62
SST A1	-.0012	.42	.020	.90	.70
A2	-.0012	.21	.020	.77	.81
A3	-.0012	.21	.011	.77	.81
A4	-.0012	0	.020	.62	1.00
A5	-.0012	0	.011	.62	1.00
B1	0	.42	.020	.90	.70
B2	0	.21	.020	.77	.81
B3	0	.21	.011	.77	.81
B4	0	0	.011	.62	1.00

TABLE III.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

[1]Failure of a stability augmenter

TABLE IV.- PILOT EXPERIENCE

Pilot	Total flight time, hr	Large jet aircraft flight time, hr	Research simulator experience, yr
A	4200	80	8
B	4000	75	7
C	9000	1800	None
D	4500	15	10
E	3600	None	6

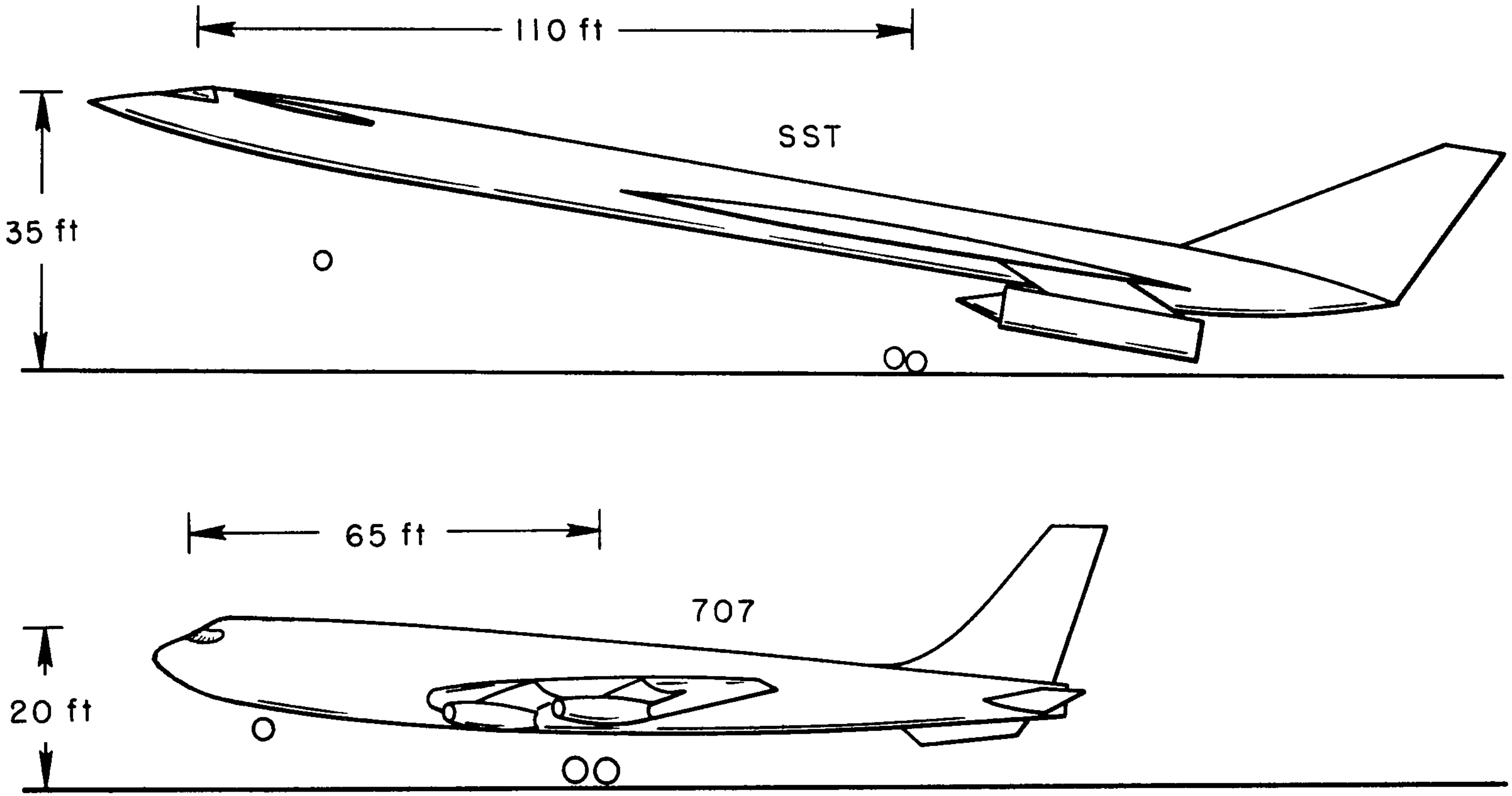
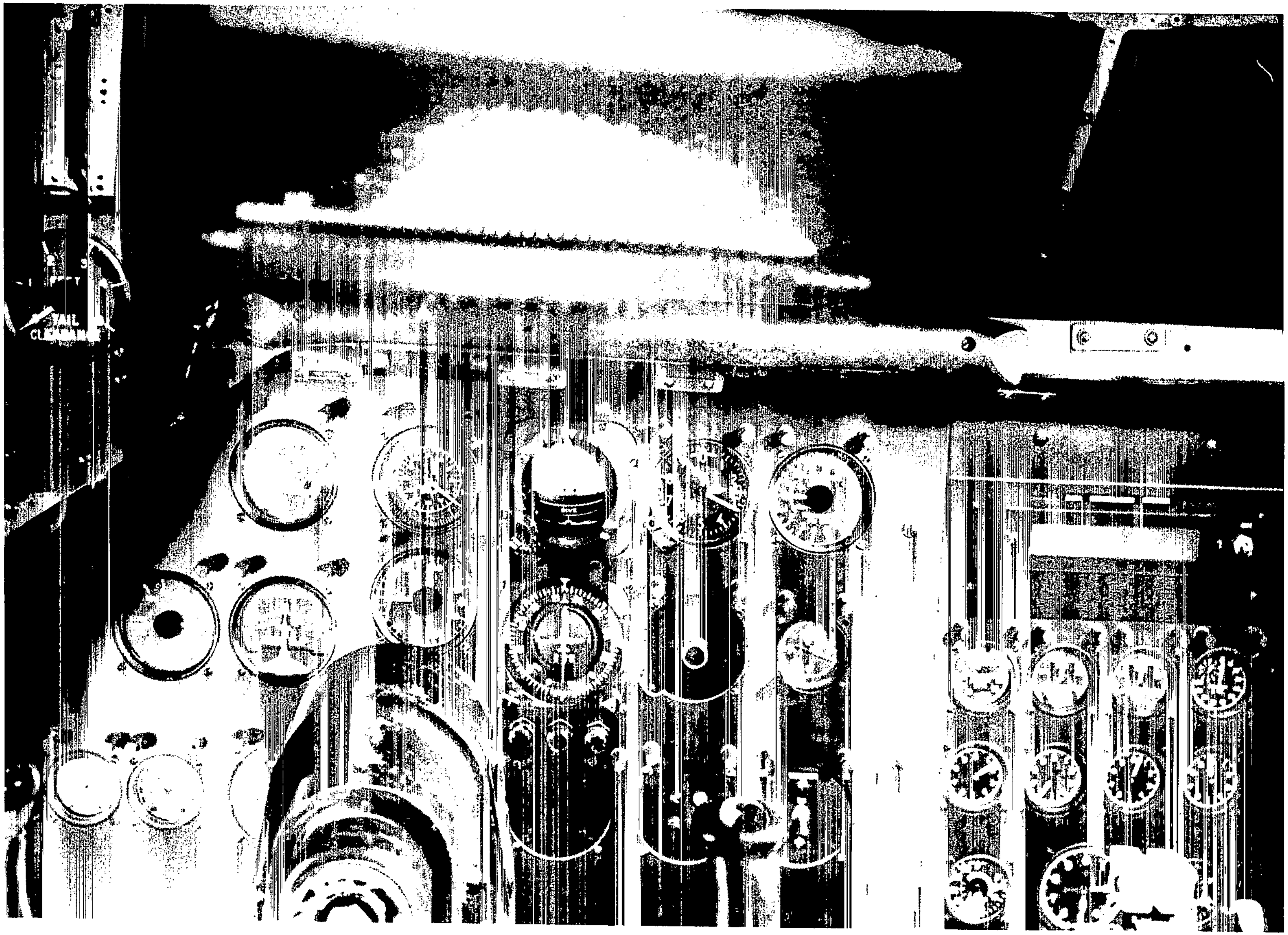


Figure 1.- Comparison of geometrical characteristics for a delta-winged supersonic transport and a current turbojet transport.



A-31061

Figure 2.- Instrument display and visual view of runway in landing-approach simulator.

A-31062

Figure 3.- DALTO visual simulator - runway model and closed-circuit TV camera.

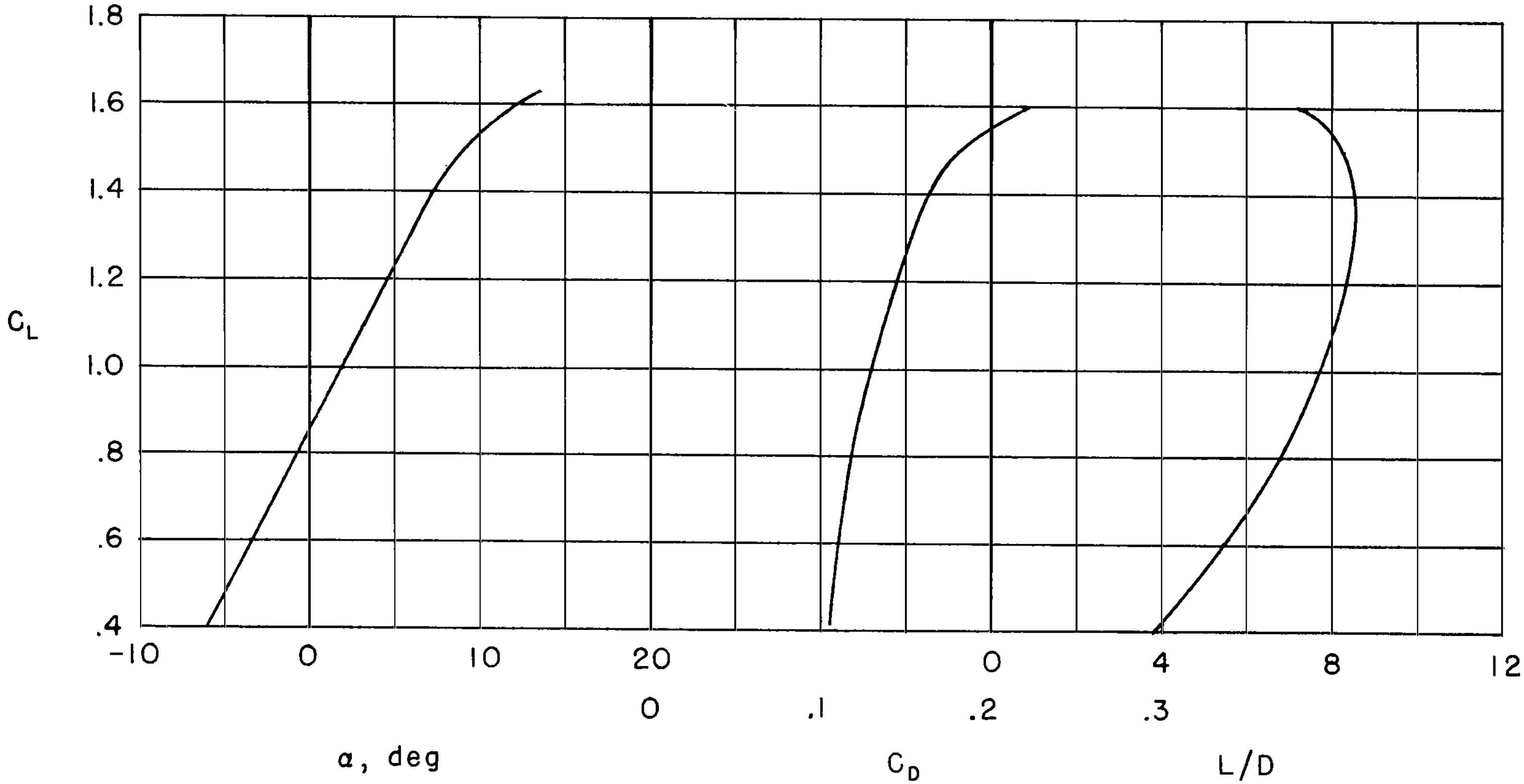


Figure 4.- Lift and drag characteristics of the simulated subsonic transport aircraft.

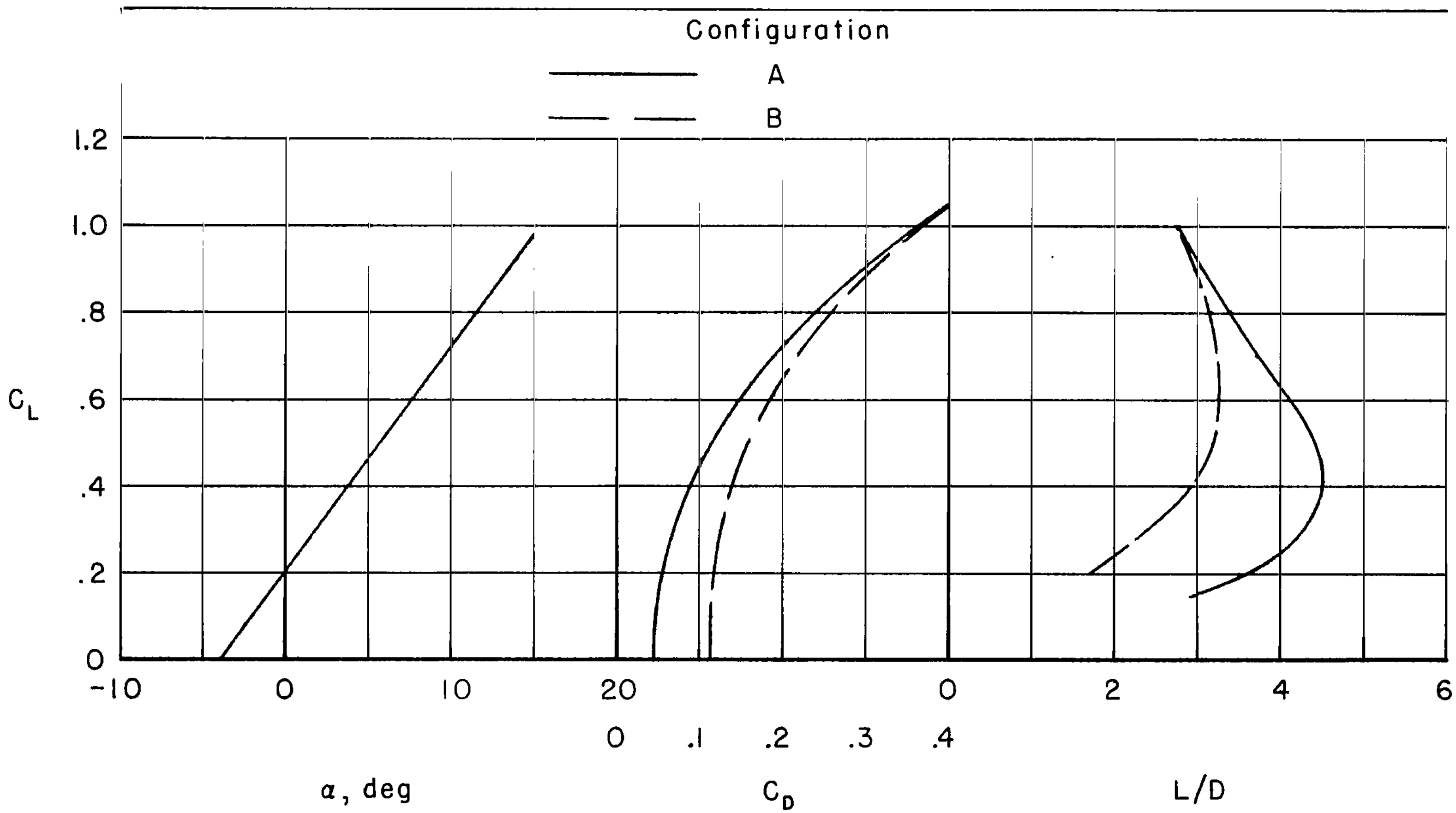


Figure 5.- Lift and drag characteristics of the simulated supersonic transport aircraft.

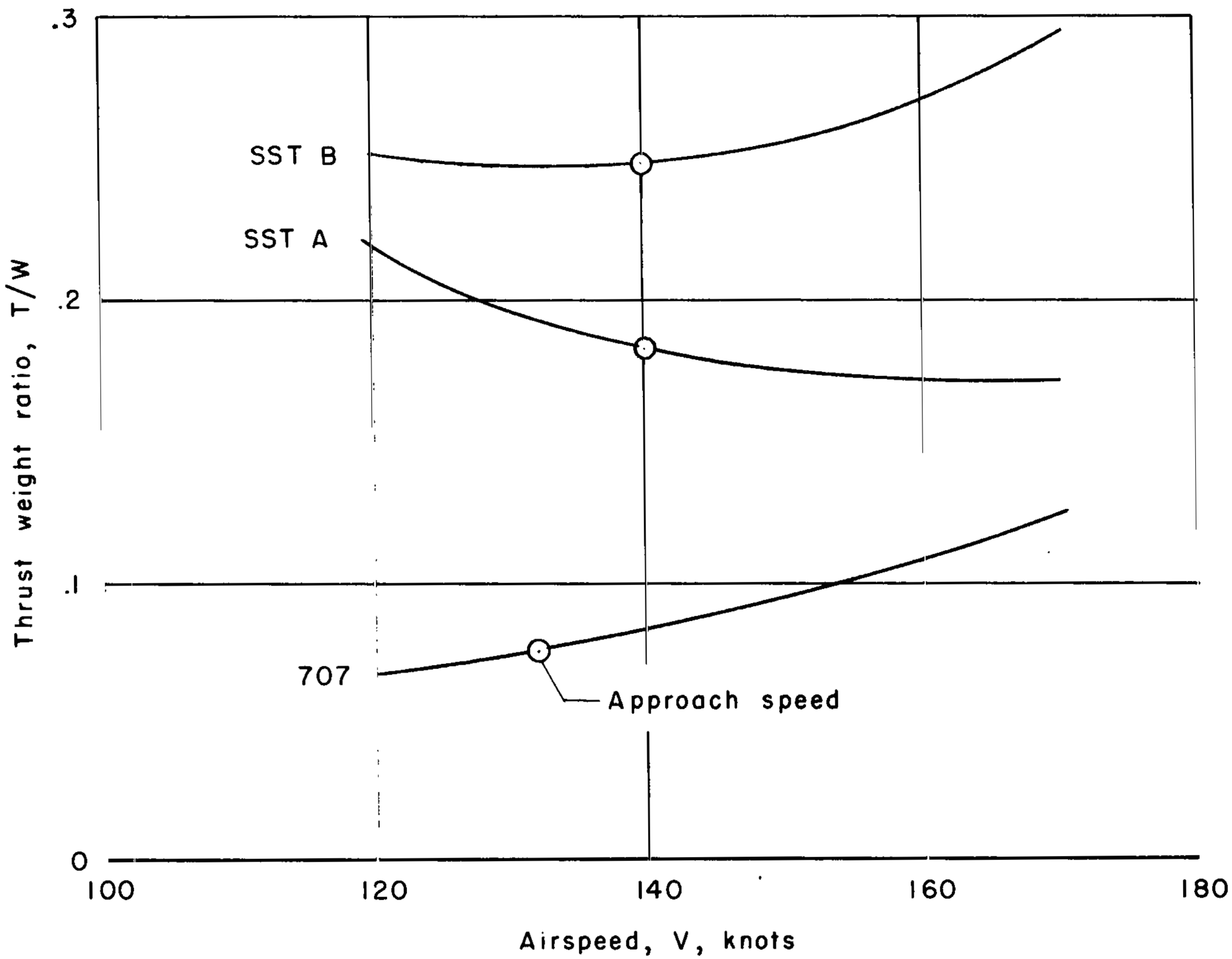


Figure 6.- Variation of thrust required with speed for the simulated airplanes on the ILS glide slope.

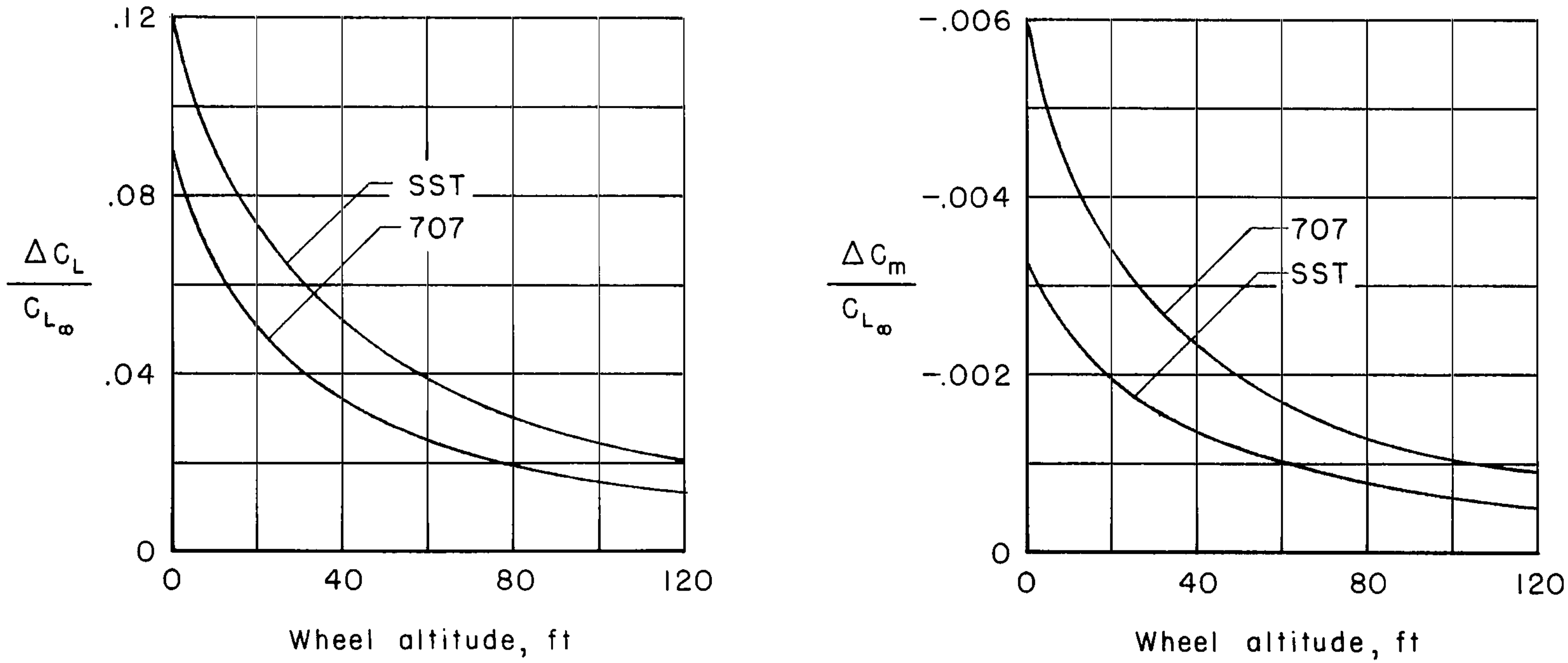


Figure 7.- Effect of presence of the ground plane on the aerodynamic characteristics of the test configurations as simulated for the landing tests.

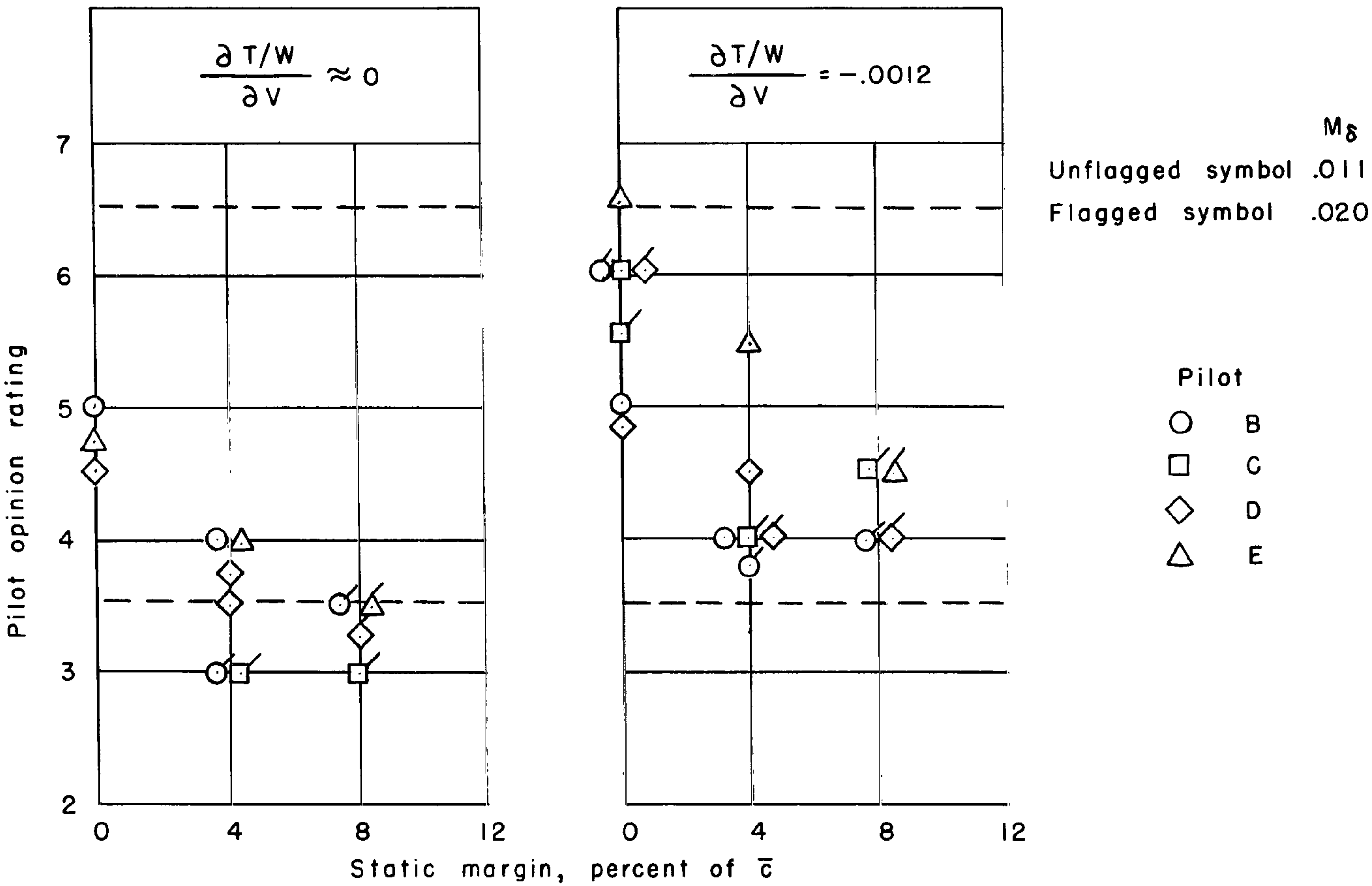


Figure 8.- Effects of variations of longitudinal stability and control parameters on pilot-opinion rating in the instrument approach task.

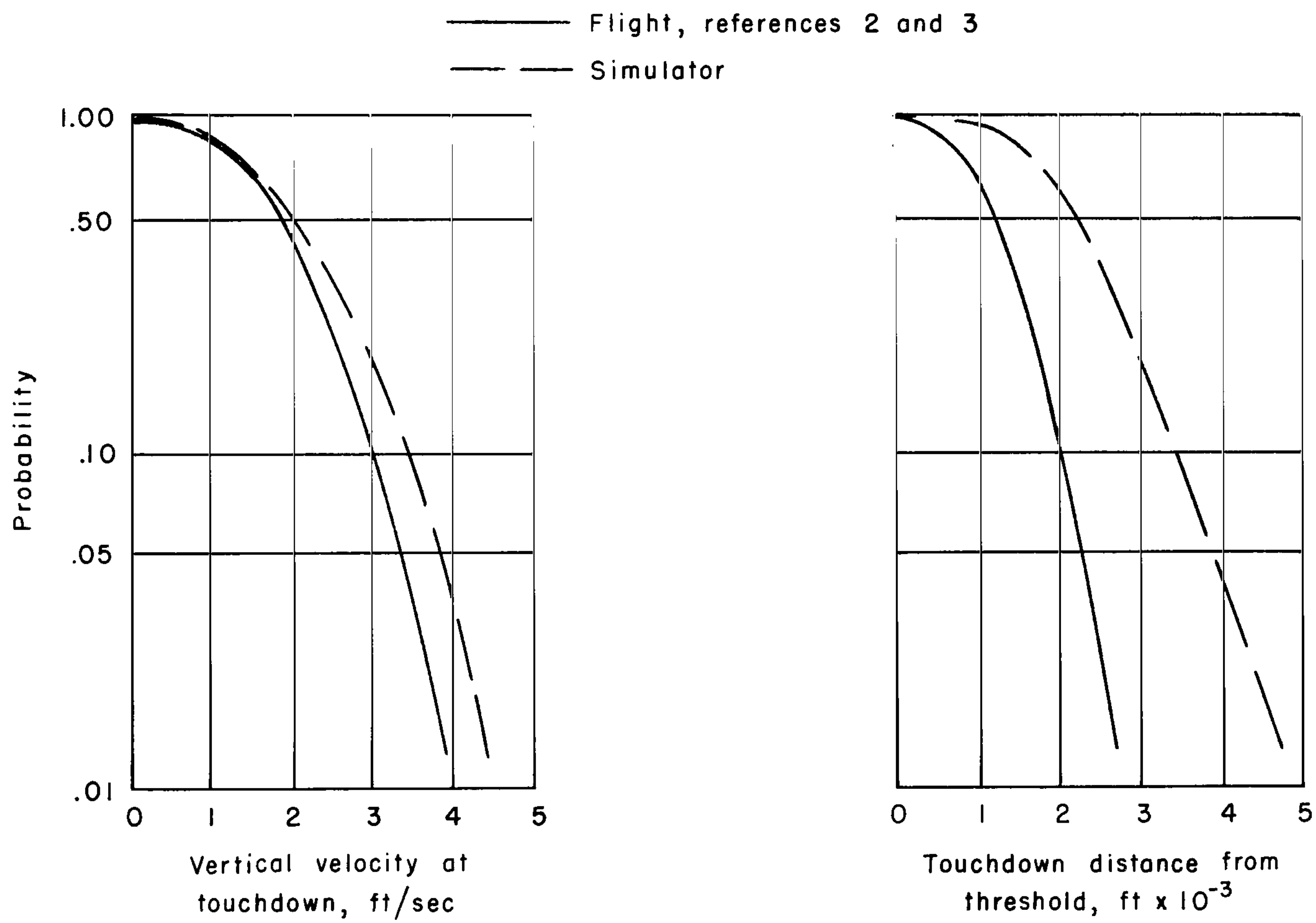


Figure 9.- Comparison of landing-performance parameters for flight and simulator landings of a turbojet transport.

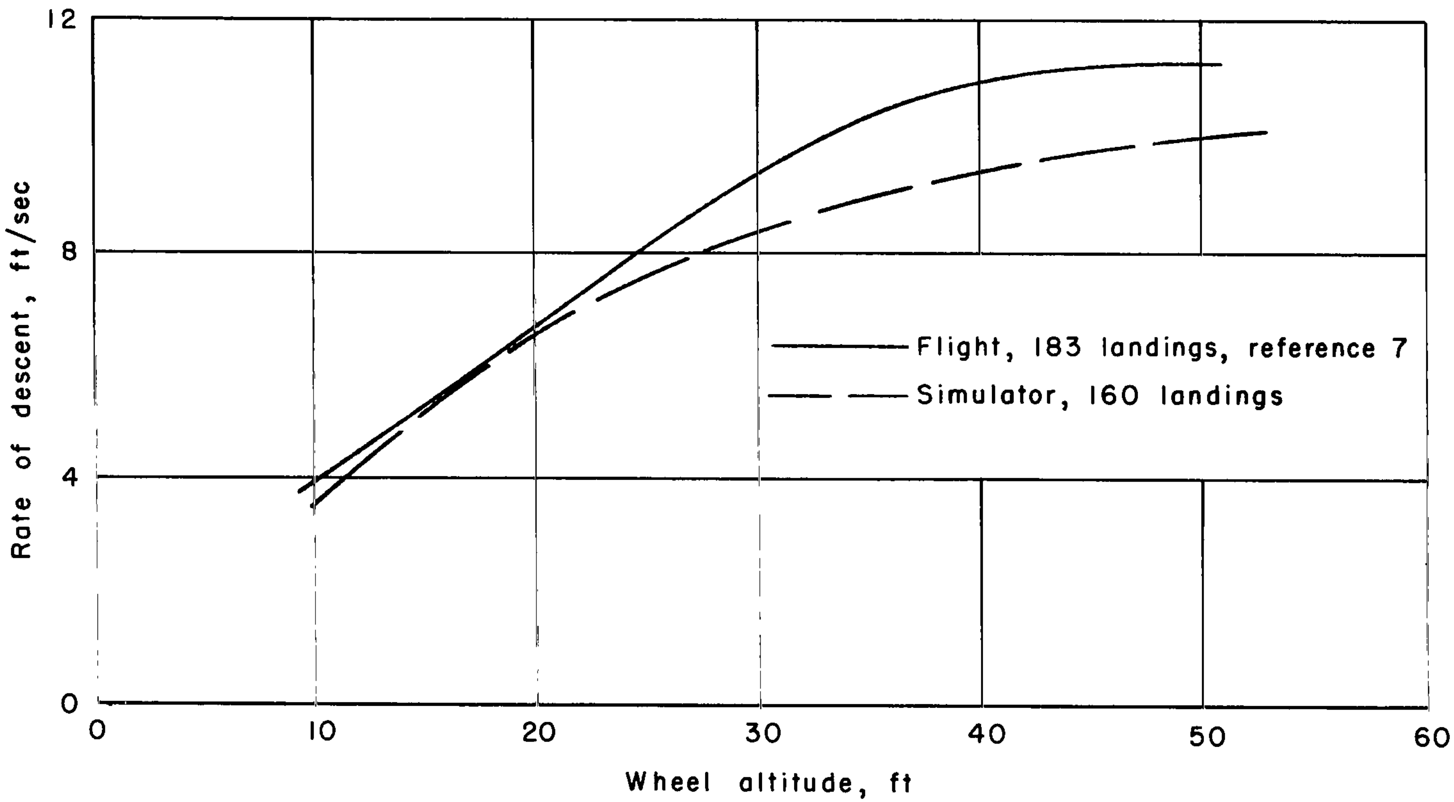


Figure 10.- Variation of rate of descent with wheel altitude from flight and simulator landings of a turbojet transport.

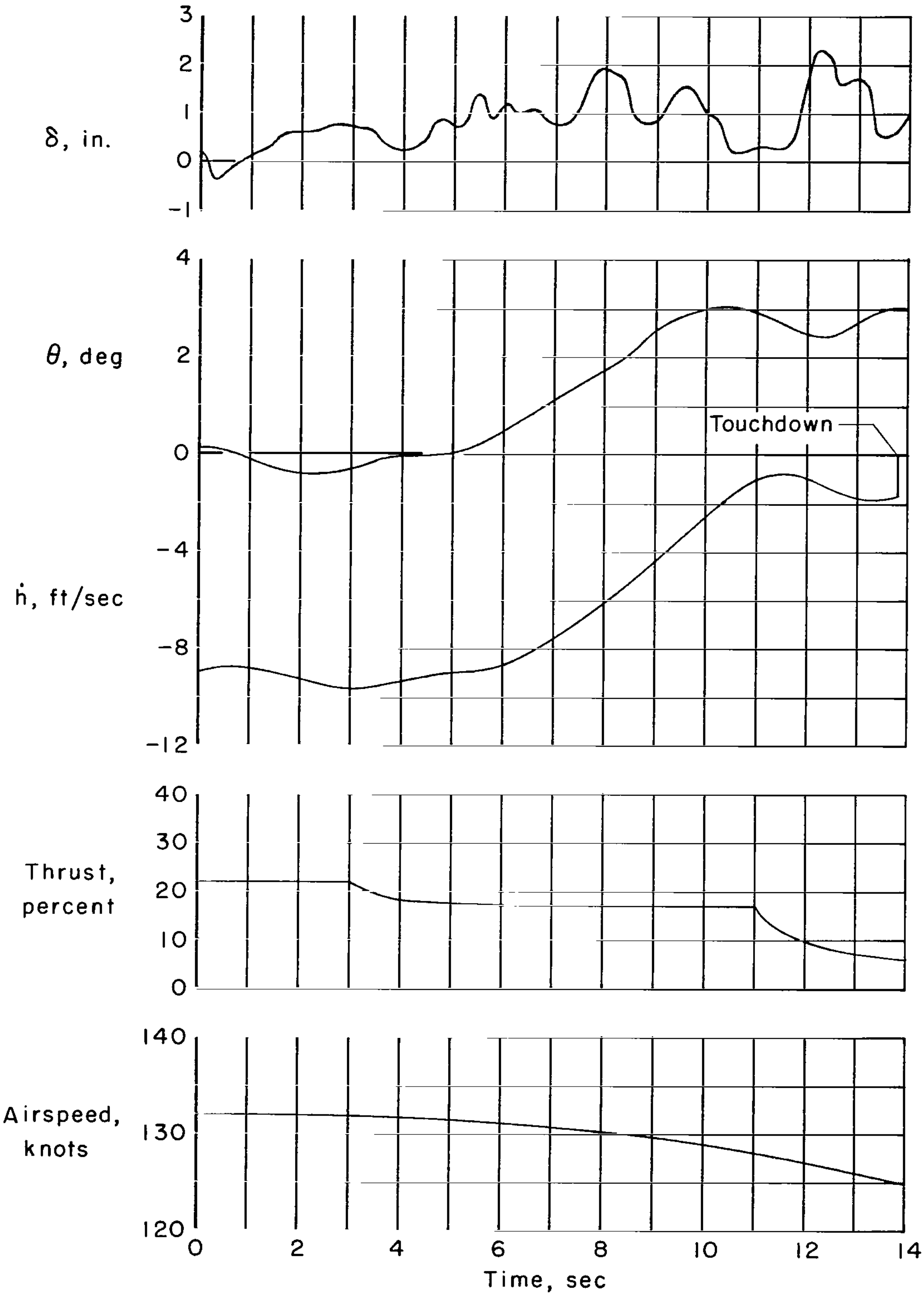


Figure 11.- Time history of flare maneuver performed with simulation of 707 airplane.

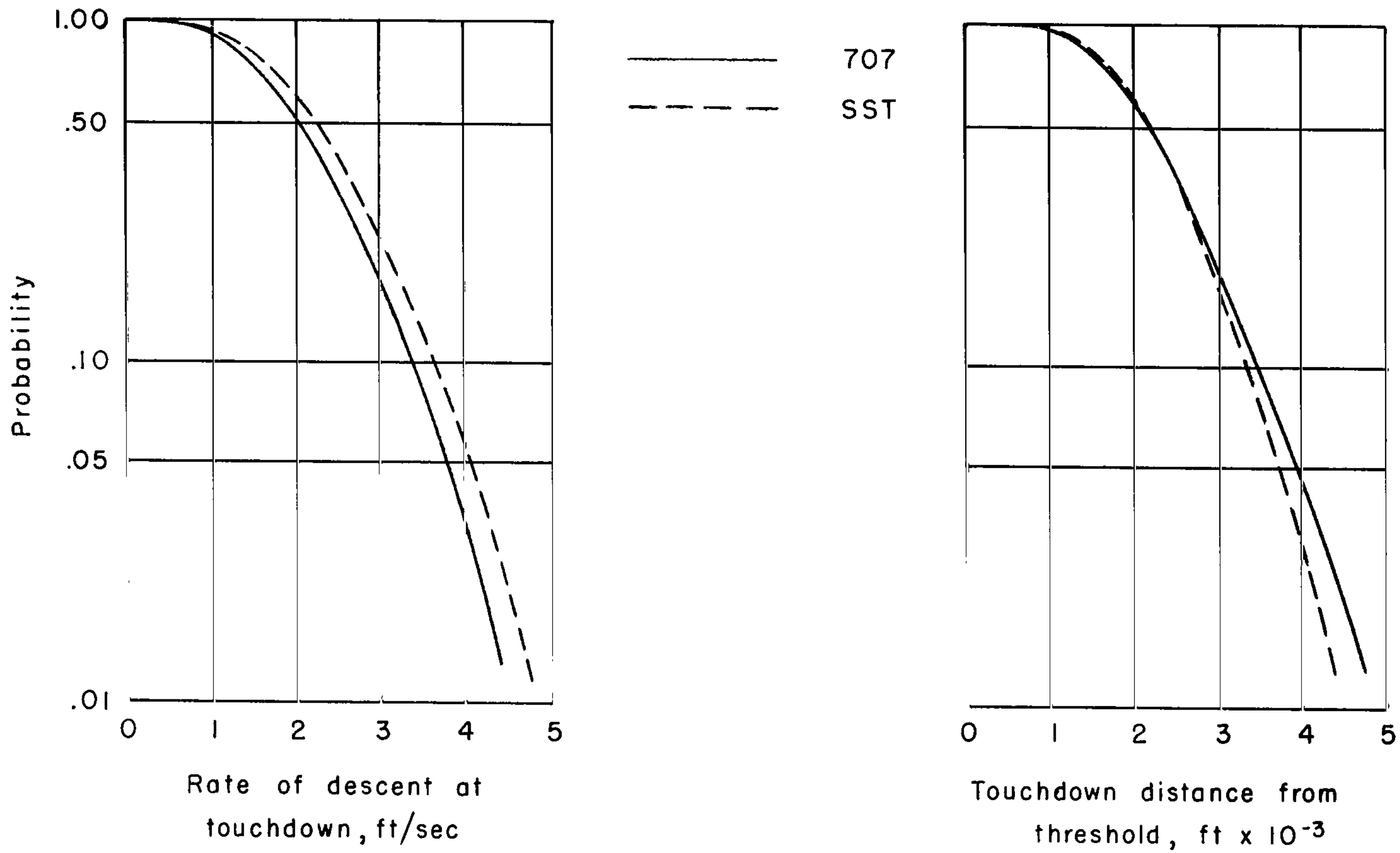


Figure 12.- Landing performance for 707 and SST simulations.

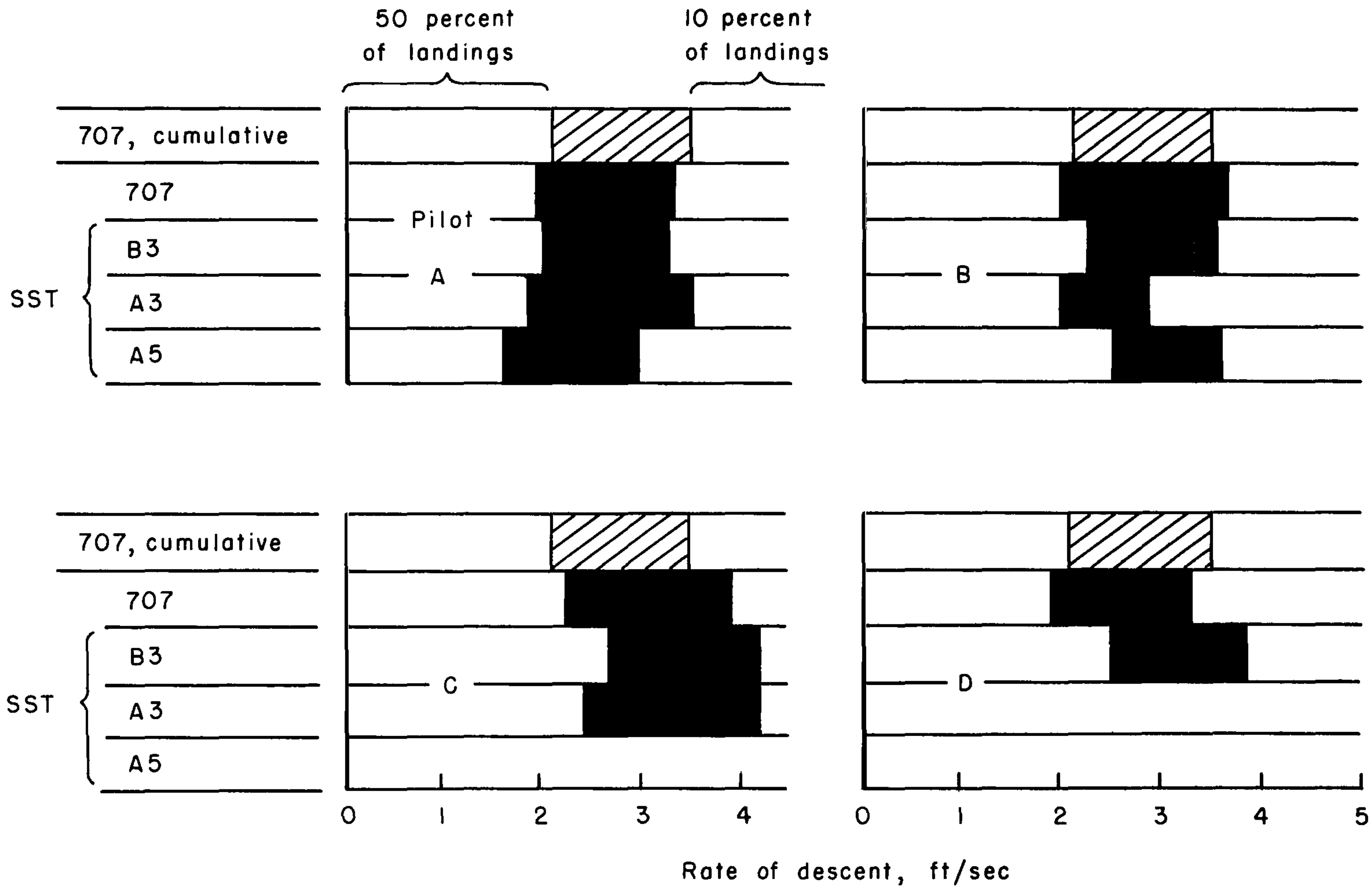


Figure 13.- Touchdown rate of descent performances from simulated landings.

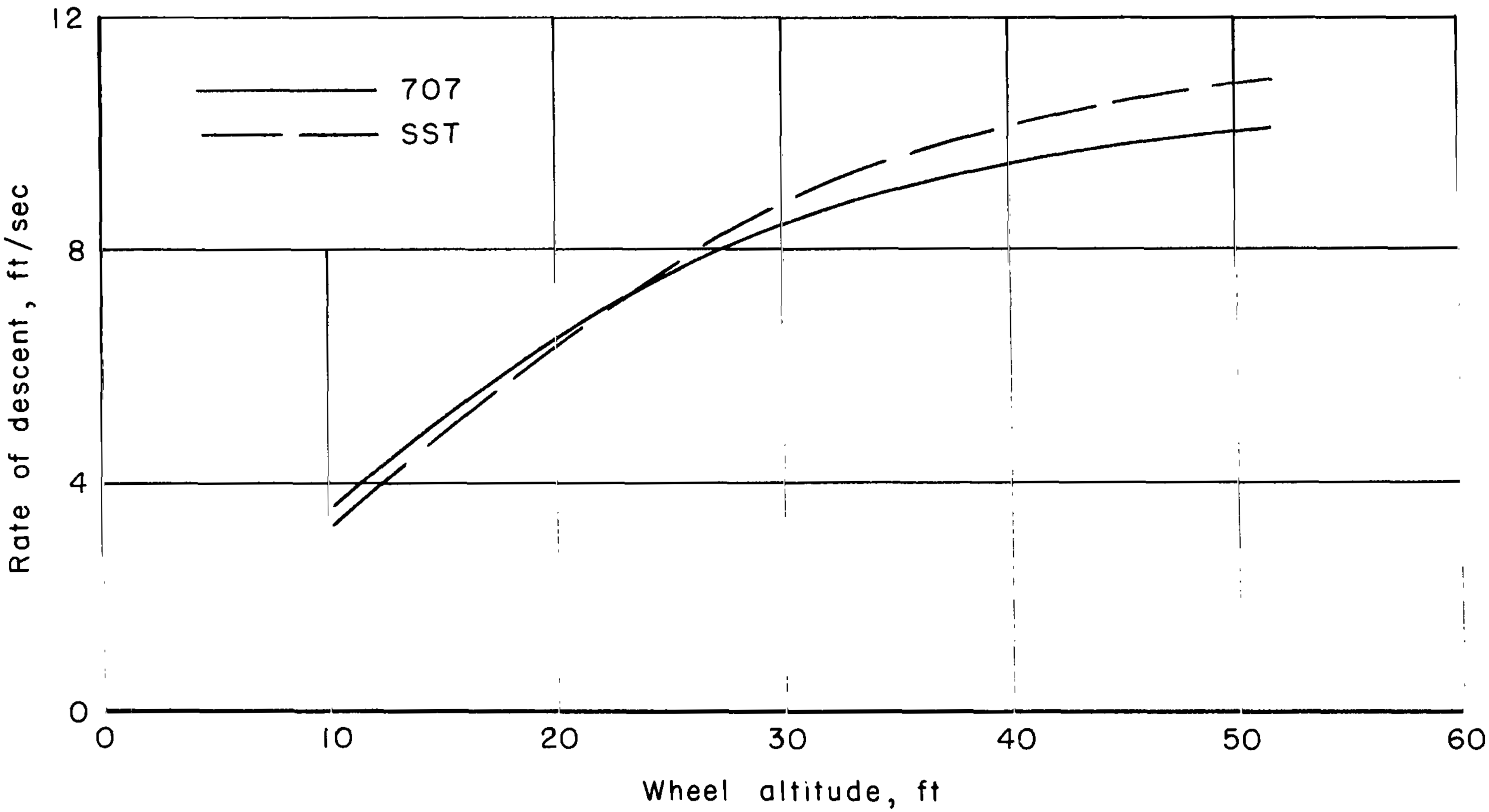


Figure 14.- Flare characteristics of simulated landings of the 707 and SST airplane.

2-17-65

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